Progresses in LGAD simulations and comparison with experimental data from UFSD2, the new 50-μm production at FBK

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Summary

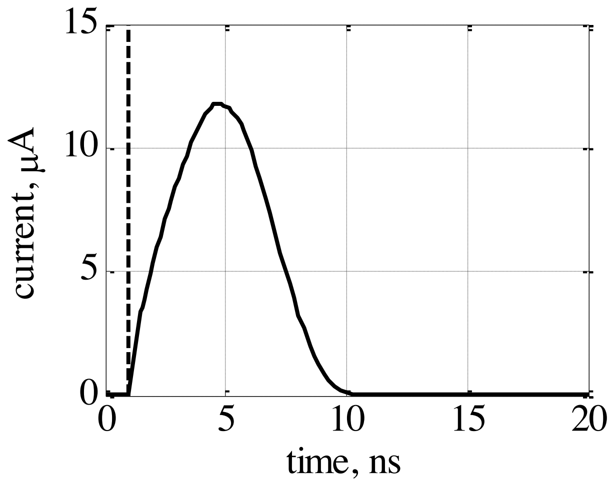
1. Short recall about **Simulation Setup** and **Models Calibration**
    - **Gain** calculation procedure
    - Description of **avalanche models**
    - Empirical model for **acceptor removal**
    - **MIP calibration** in 50-µm thick *pin* diodes with laser/heavy-ion beam

2. The **UFSD2 production** by FBK

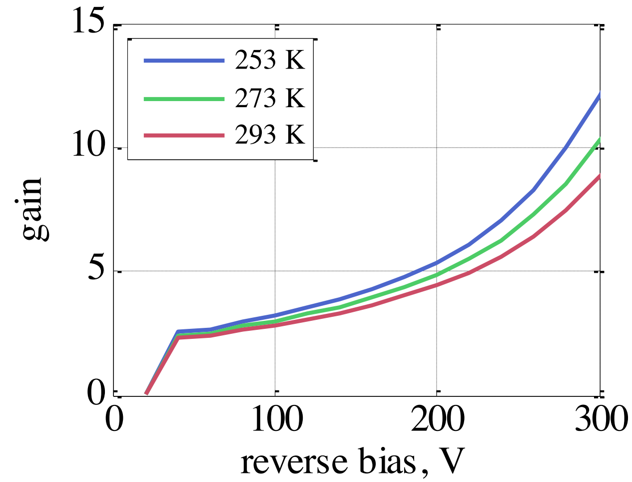
3. **Leakage current** and **Gain** simulations in UFSD2
    - **Boron/Gallium** implants
    - **Carbonated/non-carbonated** wafers

4. **Electric Field** and **Inter-pad Efficiency** simulations in UFSD2
    - Strip sensor **signal scan**

Simulation setup



$$G(V) = \frac{Q_{\text{LGAD}}(V)}{Q_{pin}(V)}$$



The generation/recombination (GR) models accounted for in the simulation are:

- **Avalanche** generation
- **Shockley-Read-Hall** (SRH)
- **Band-to-band tunneling** (BTBT)

where three different multiplication models have been tested

Simulation setup

van Overstraeten: $\alpha_{n,p}(E) = \gamma \cdot A_{n,p} \cdot \exp\left(-\gamma \frac{B_{n,p}}{E}\right)$

where: $A_n = 7.030\times10^5\ \text{cm}^{-1}$, $B_n = 1.231\times10^6\ \text{V/cm}$, $A'_p = 1.582\times10^6\ \text{cm}^{-1}$ and $B_p = 2.036\times10^6\ \text{V/cm}$ (or $A'_p = 6.710\times10^5\ \text{cm}^{-1}$ and $B'_p = 1.693\times10^6\ \text{V/cm}$ in low-field conditions)

Massey: $\alpha_{n,p}(E) = A_{n,p} \cdot \exp\left(-\frac{B_{n,p}(T)}{E}\right)$

where: $A_n = 4.43\times10^5\ \text{cm}^{-1}$, $A_p = 1.13\times10^6\ \text{cm}^{-1}$, $B_n(T) = C_n + D_n \cdot T$ and $B_p(T) = C_p + D_p \cdot T$, with $C_n = 9.66\times10^5\ \text{V}\cdot\text{cm}^{-1}$, $C_p = 1.71\times10^6\ \text{V}\cdot\text{cm}^{-1}$, $D_n = 4.99\times10^2\ \text{V}\cdot\text{cm}^{-1}\cdot\text{K}^{-1}$ and $D_p = 1.09\times10^3\ \text{V}\cdot\text{cm}^{-1}\cdot\text{K}^{-1}$

Okuto: $\alpha_{n,p}(E) = A_{n,p} \cdot \left(1 + (T - 300)C_{n,p}\right) \cdot E \cdot \exp\left(-\left(\frac{B_{n,p}\cdot\left(1+(T-300)D_{n,p}\right)}{E}\right)^2\right)$

where: $A_n = 0.426\ \text{V}^{-1}$, $B_n = 4.81\times10^5\ \text{V/cm}$, $A_p = 0.243\ \text{V}^{-1}$, $B_p = 6.53\times10^5\ \text{V/cm}$, $C_n = 3.05\times10^{-4}\ \text{K}^{-1}$, $C_p = 5.35\times10^{-4}\ \text{K}^{-1}$, $D_n = 6.86\times10^{-4}\ \text{K}^{-1}$ and $D_p = 5.67\times10^{-4}\ \text{K}^{-1}$

Simulation setup

Other transport models implemented in the drift-diffusion (DD) framework are the **Shockley-Read-Hall (SRH)** process, with generation rate

$$G_{\mathrm{SRH}} = \frac{n \cdot p - n_i^2}{\tau_p\left(n - n_i \cdot \exp(-E_t/k_{\mathrm{B}}T)\right) + \tau_n\left(p - n_i \cdot \exp(E_t/k_{\mathrm{B}}T)\right)}$$

and the **band-to-band tunneling (BTBT)**, where the rate is

$$G_{\mathrm{BTBT}}(E) = A \cdot E^2 \cdot \exp\left(-\frac{B}{E}\right)$$

Concerning the **effects of radiation** we used the empirical law

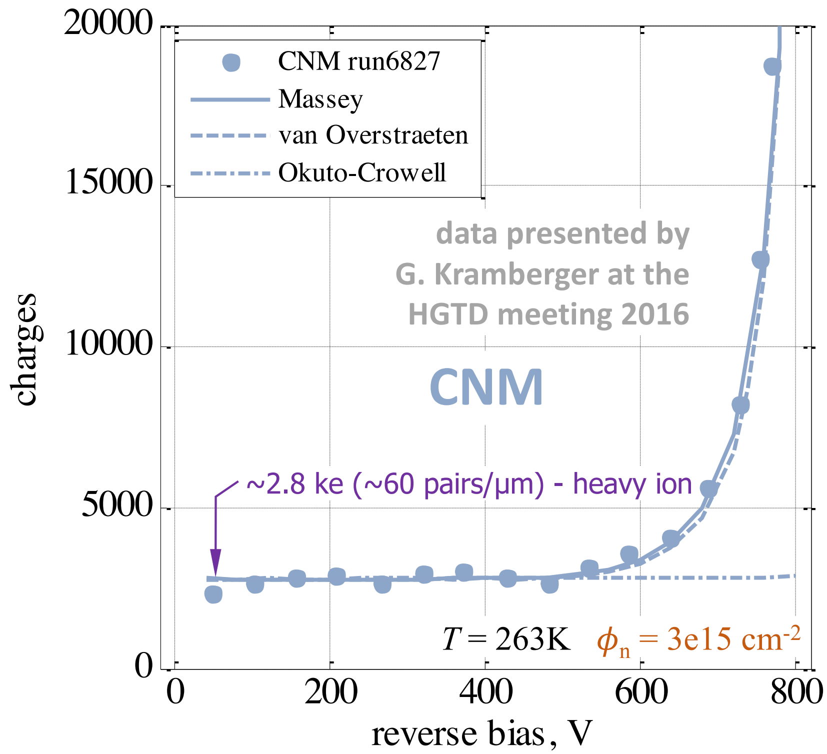
$$N_{\mathrm{A}}(\phi) = g_{\mathrm{eff}} \cdot \phi + N_{\mathrm{A}}(0) \cdot \mathrm{e}^{-c(N_{\mathrm{A}}(0)) \cdot \phi}$$

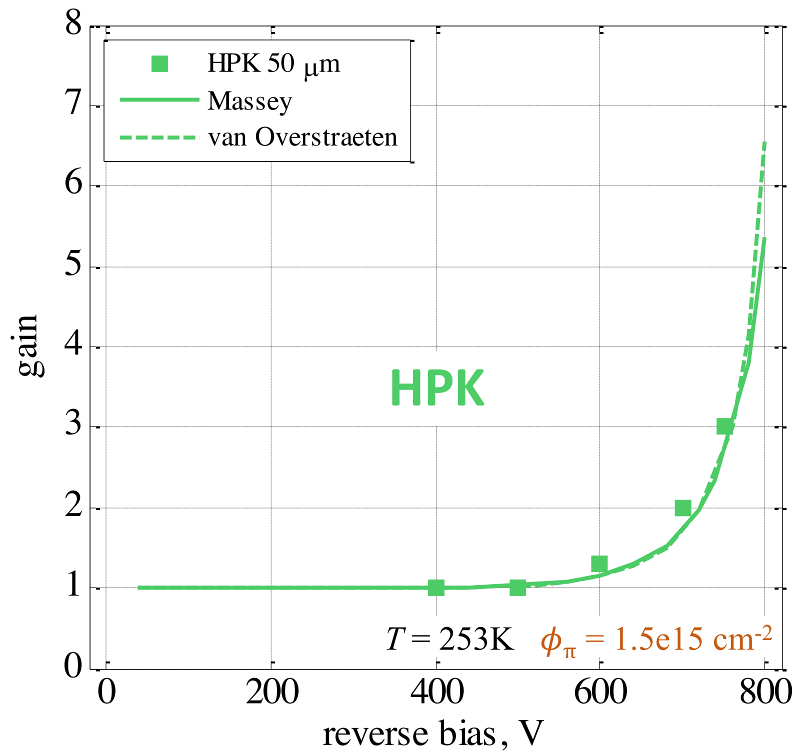
accounting for both **acceptor creation** and **initial acceptor removal** mechanisms, where ϕ is the fluence, $g_{\mathrm{eff}} \cong 0.02\ \mathrm{cm}^{-1}$ and

$$c(N_{\mathrm{A}}(0), x) = \alpha \cdot N_{\mathrm{A}}(0, x)^{-\beta}$$

Model calibration

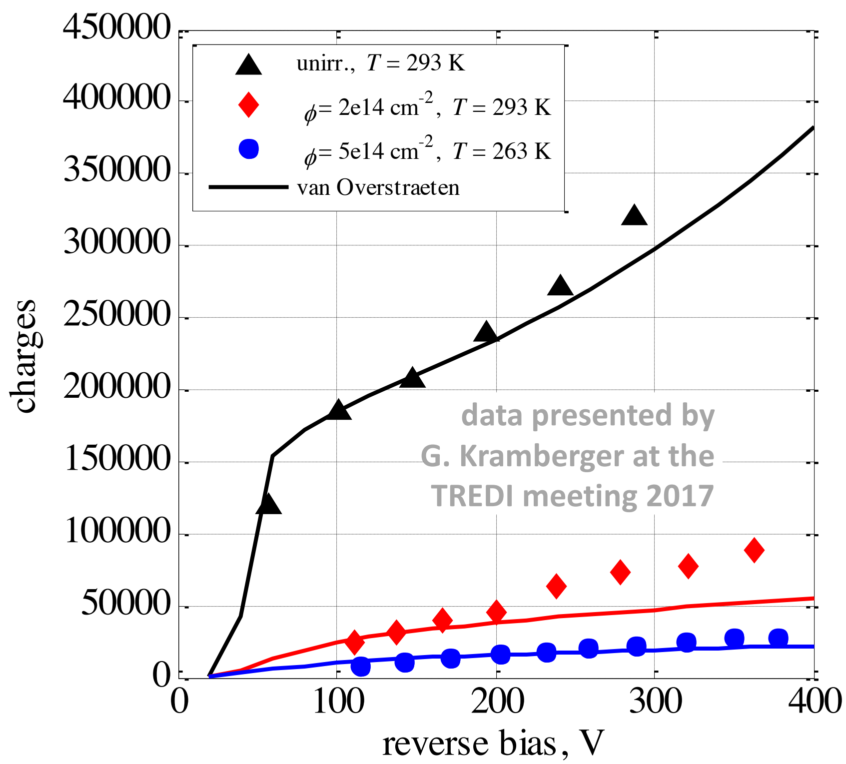
MIP calibration on measurements from irradiated 50 µm *pin* diodes by CNM and HPK





Model calibration

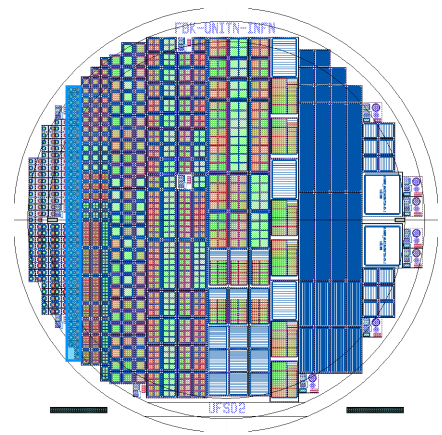
Example: irradiated **300 µm** UFSD by **FBK** at different **fluence** and **temperature**

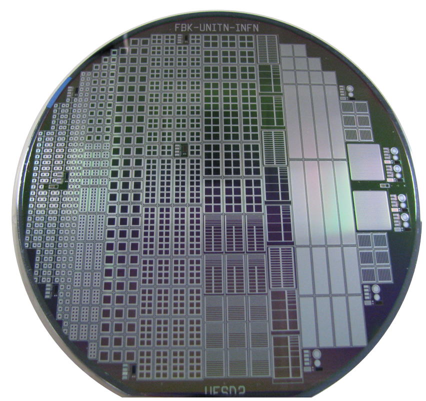


- Simulation of both ***pin*** and **LGAD** diodes
- Measurements from **Ljubljana**
- Simulated heavy-ion at **~60 pairs/µm**
- **Acceptor removal** parametrization

UFSD2 production

Wafer #	Dopant	Gain dose	Carbon
1	Boron	0.98	
2	Boron	1.00	
3	Boron	1.00	
4	Boron	1.00	low
5	Boron	1.00	High
6	Boron	1.02	low
7	Boron	1.02	High
8	Boron	1.02	
9	Boron	1.02	
10	Boron	1.04	
11	Gallium	1.00	
14	Gallium	1.04	
15	Gallium	1.04	low
16	Gallium	1.04	High
18	Gallium	1.08	



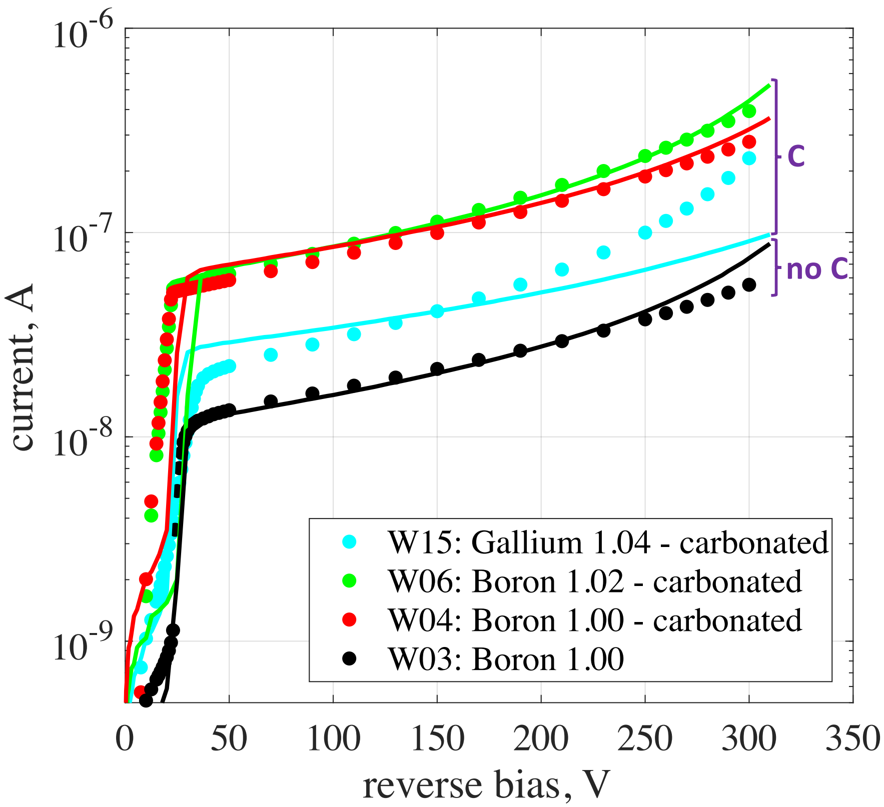


UFSD2 simulations - I

Non-irradiated 1 x 1 mm^2 **pads**

Leakage Current

(on wafer)



- Simulations with **van Overstraeten - de Man** avalanche model and **focused laser beam**
- Highly realistic **segmentation** *p* and *n* **profiles** (Montecarlo simulations)
- **Gain layer** implant profiles coming from ***C*(*V*) measurements**

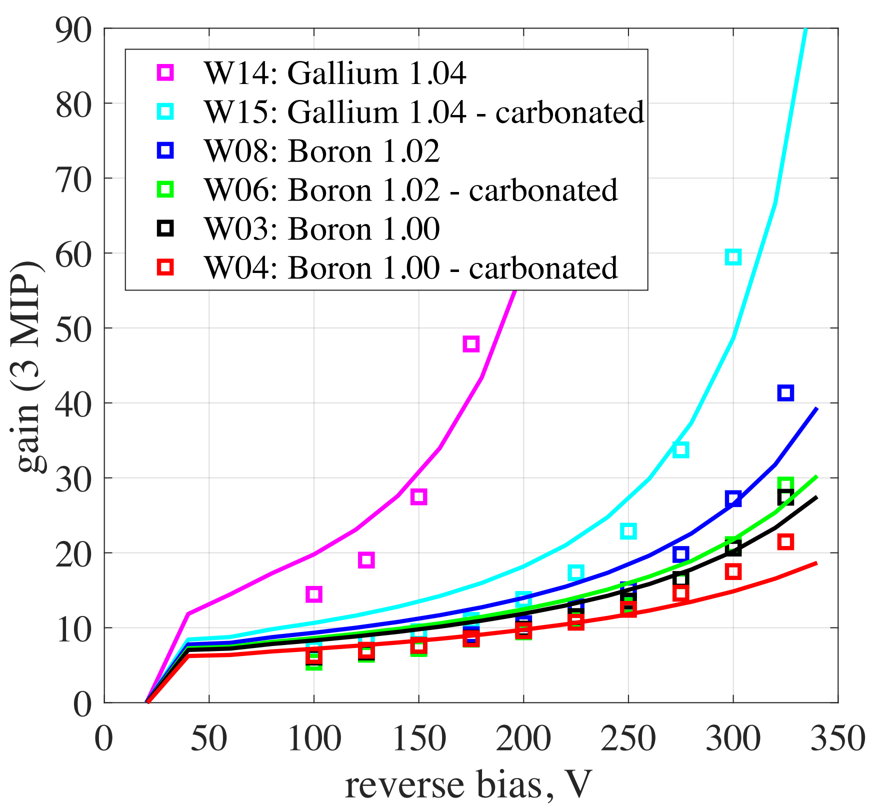
⇒ **Non-carbonated devices show a lower leakage current**

UFSD2 simulations - I

Non-irradiated 1 x 1 mm^2 **pads**

Gain

(laser setup)



- Simulations with **van Overstraeten - de Man** avalanche model and **focused laser beam**
- Highly realistic **segmentation** *p* and *n* **profiles** (Montecarlo simulations)
- **Gain layer** implant profiles coming from ***C*(*V*) measurements**

⇒ **Higher gallium/boron dose** corresponds to **higher gain**

⇒ **Carbon implantation** produces a **gain reduction**, especially in **Ga-doped** wafers

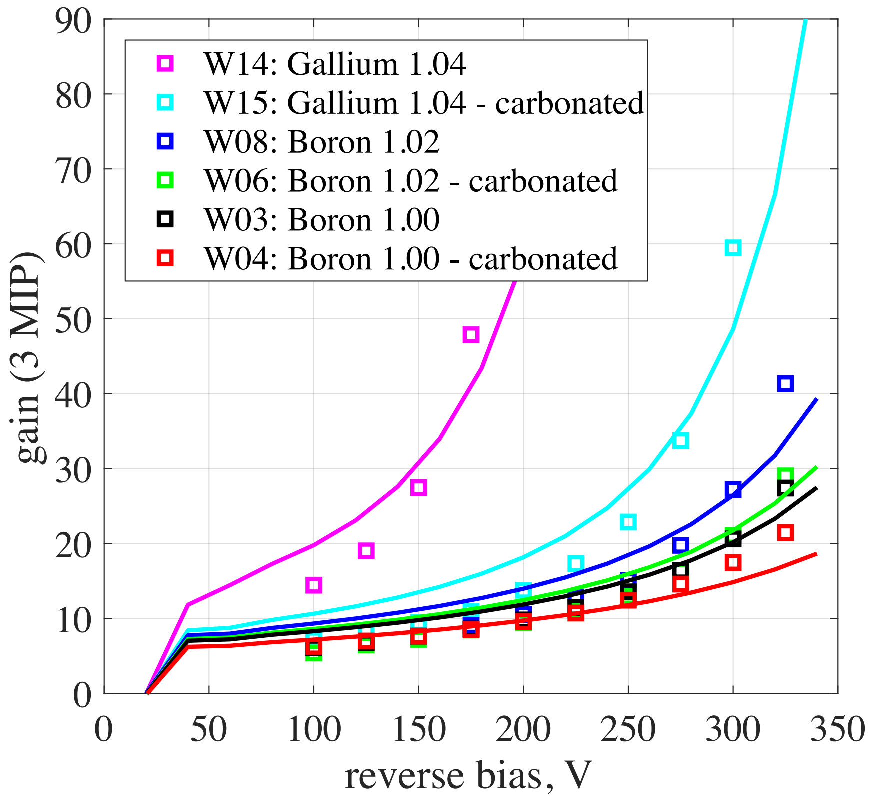
⇒ Possible **gallium/boron segregation** via **carbon clustering**

UFSD2 simulations - I

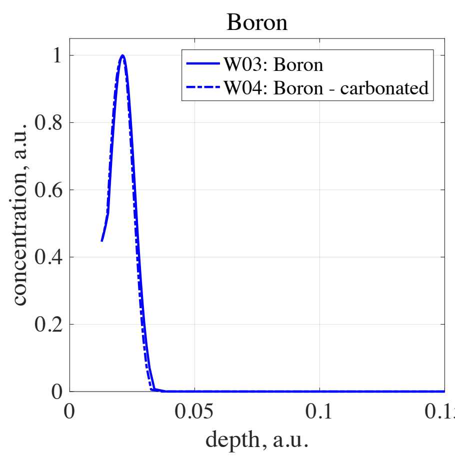
Non-irradiated 1 x 1 mm^2 **pads**

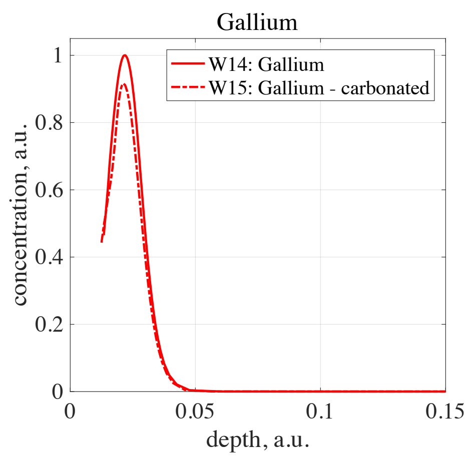
Gain

(laser setup)



As stated by measured profiles…





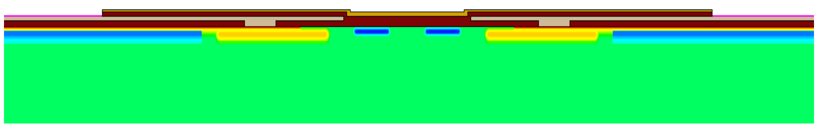
0.5% loss at peak

8.5% loss at peak

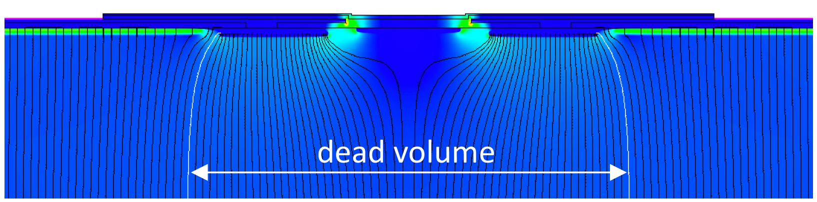
UFSD2 simulations - II

Non-irradiated ~200-µm pitch **strips**

Electric Field



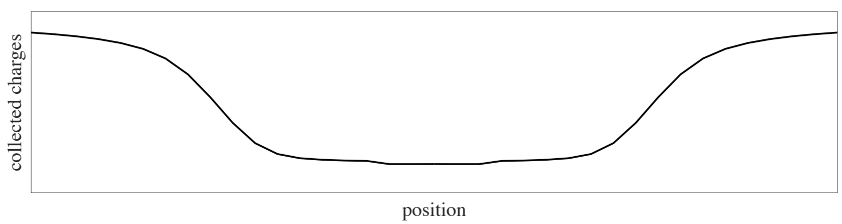
UFSD2 layout has been implemented



From **Poisson equation**

$$\nabla_{\mathbf{r}} E = \frac{\rho(\mathbf{r}, t)}{\epsilon}$$

one computes the **electric field**



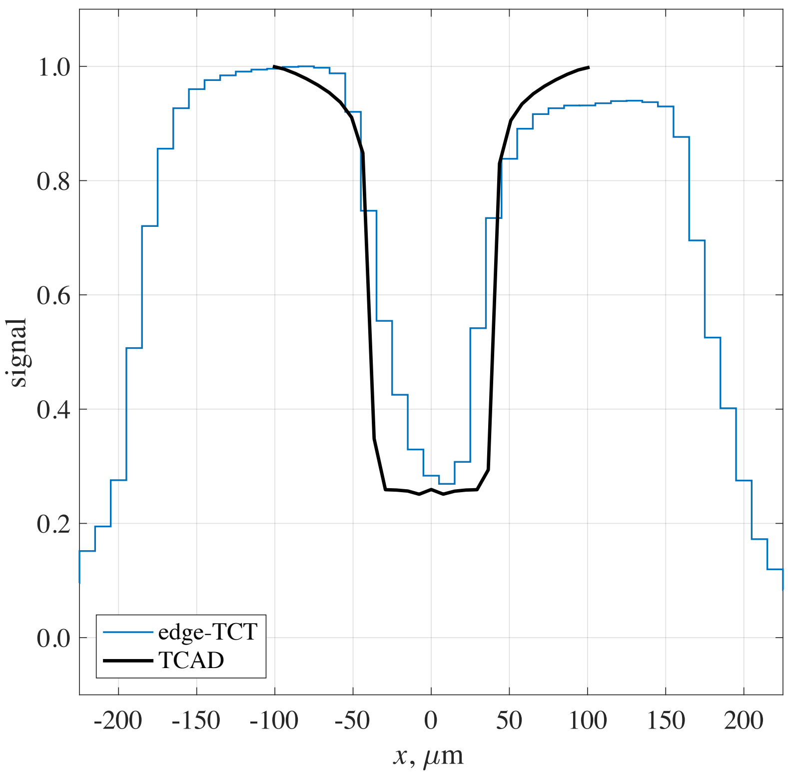
Signal scan directly derives from the trend of **field lines** in the active region

UFSD2 simulations - II

Non-irradiated ~200-µm pitch **strips**

Inter-Strip Signal

(edge-TCT setup)



- Strip from **W8** (**Boron 1.02**) at V_{bias} **= 230 V** and laser calibrated for **1 MIP**
- Simulation with **Massey** model and **focused laser**

⇒ The **slope** is pretty well reproduced

⇒ **TCT laser** has a spot ~**15-µm** wide while in simulations it is ideally focused

⇒ **FWHM dead area: ~75 µm** (measured)
~78 µm (simulated)

Conclusions

The simulation setup used to **calibrate the TCAD framework** and to **investigate the UFSD1 production** was tested here on the new **UFSD2 sensors**

By implementing the **real gain profiles** it is possible to accurately reproduce the most important **static features of UFSD2**, like **leakage current** and **gain**

From the **electric field** calculation it is also possible to infer the **sensor efficiency** in the **inter-pad** region having, therefore, an estimation of the **fill-factor**

⇒ What's next?

- We are waiting data from the irradiation campaign on **UFSD-2 sensors** in order to test **multiplication** and **radiation-related** models on **Gallium-doped** and **carbonated** devices

Acknowledgments

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